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Chang

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(54) **LIGHT-EMITTING DIODE LIGHTING DEVICE**

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H01L 25/075 (2006.01)

H01L 33/42 (2010.01)

H01L 33/50 (2010.01)

(52) **U.S. Cl.**

CPC **H01L 25/0753** (2013.01); **H01L 33/42** (2013.01); **H01L 33/50** (2013.01)

(58) **Field of Classification Search**

CPC ... H01L 33/00; H01L 25/0753; H01L 27/153; H01L 33/20; H01L 33/62

USPC 257/85, 88, 98, 99

See application file for complete search history.

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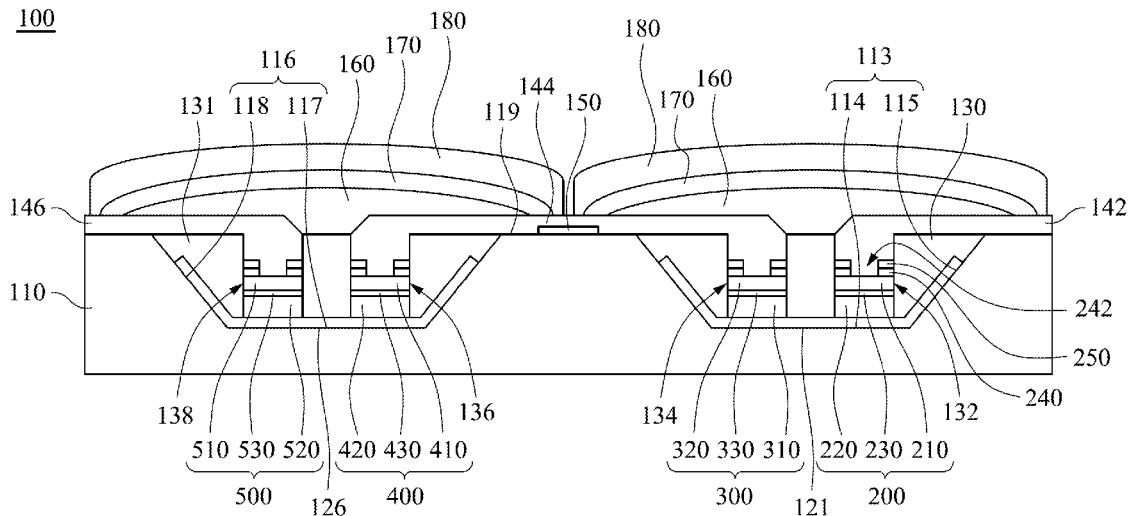
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ABSTRACT

A light-emitting diode (LED) lighting device includes a substrate, a first bottom electrode, a bottom transparent isolation layer, a first vertical LED, a second vertical LED, a first top transparent electrode, and a second top transparent electrode. The substrate has a first recess therein. The first bottom electrode is disposed in the first recess and is reflective. The first vertical LED and the second vertical LED are disposed in the first recess and on the first bottom electrode. The first bottom transparent isolation layer is disposed in the first recess. The first top transparent electrode is electrically connected to the first vertical LED. The second top transparent electrode is electrically connected to the second vertical LED. The first top transparent electrode, the second top transparent electrode, and the first bottom electrode cooperate to electrically connect the first vertical LED and the second vertical LED in series.

23 Claims, 8 Drawing Sheets



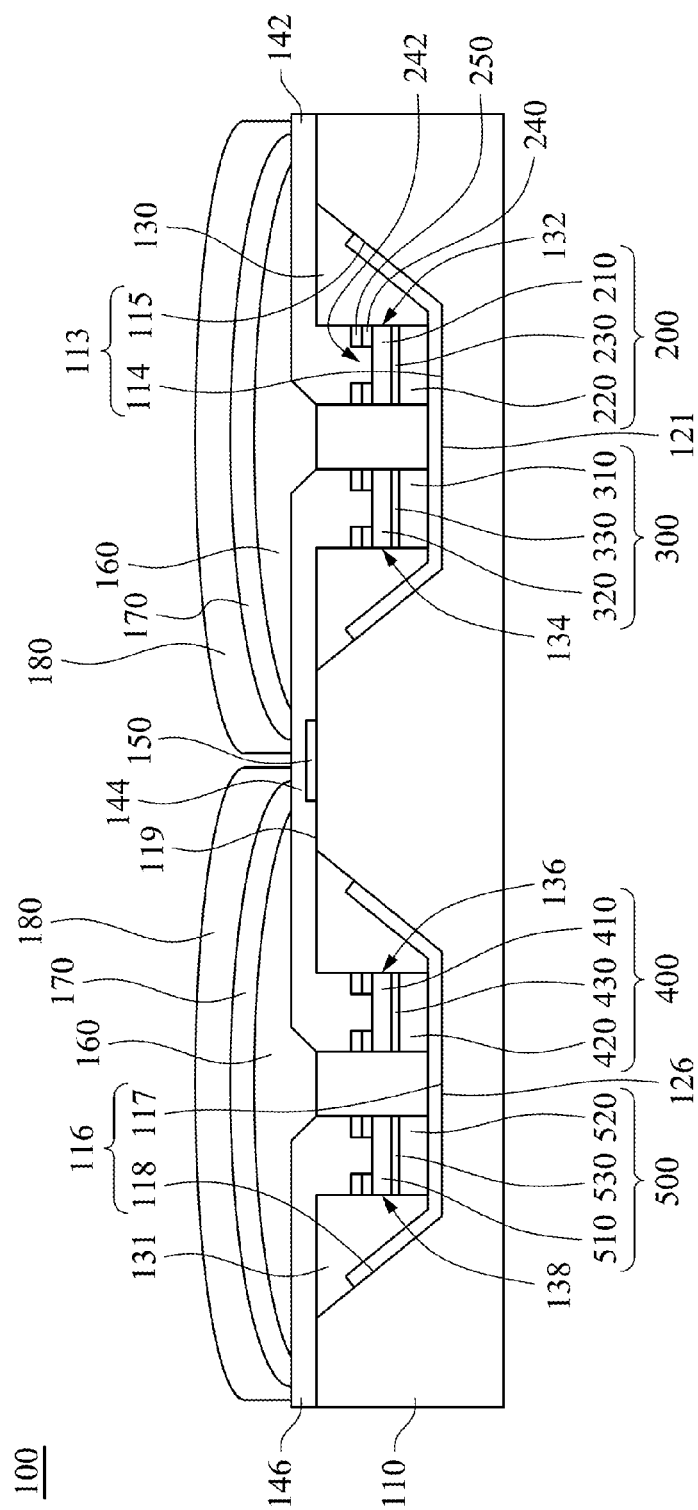


Fig. 1

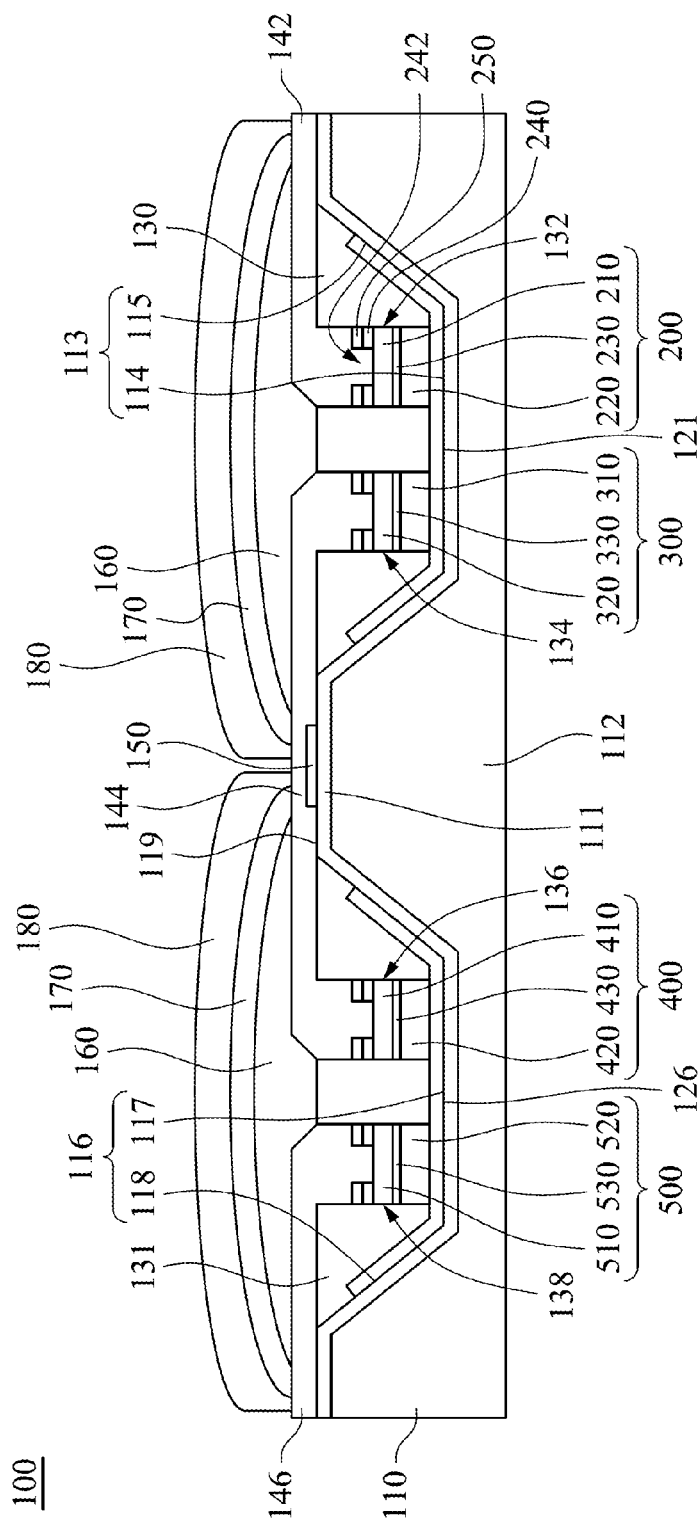


Fig. 2

100

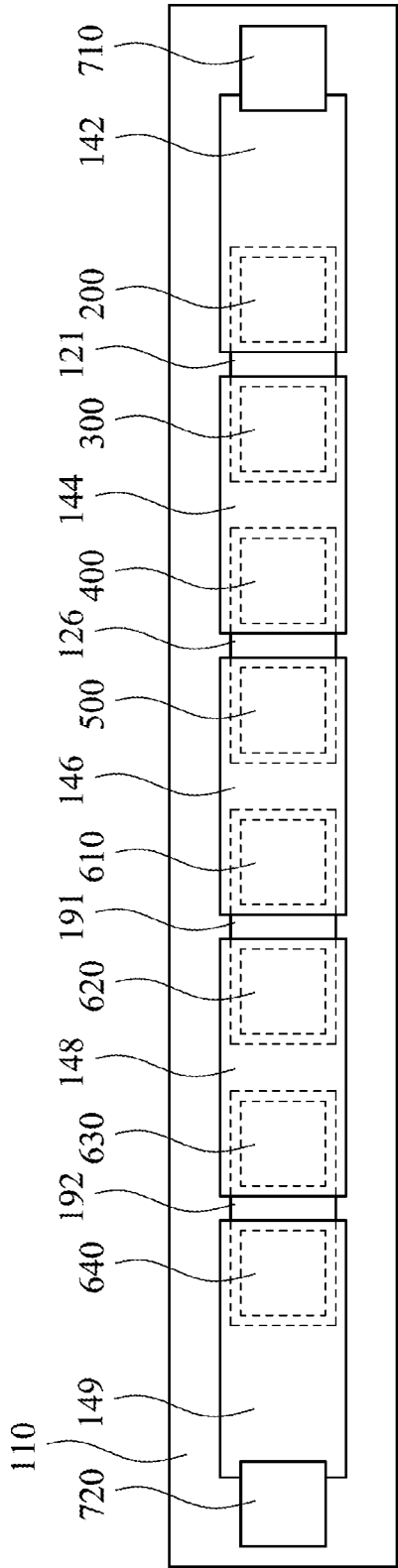


Fig. 3A

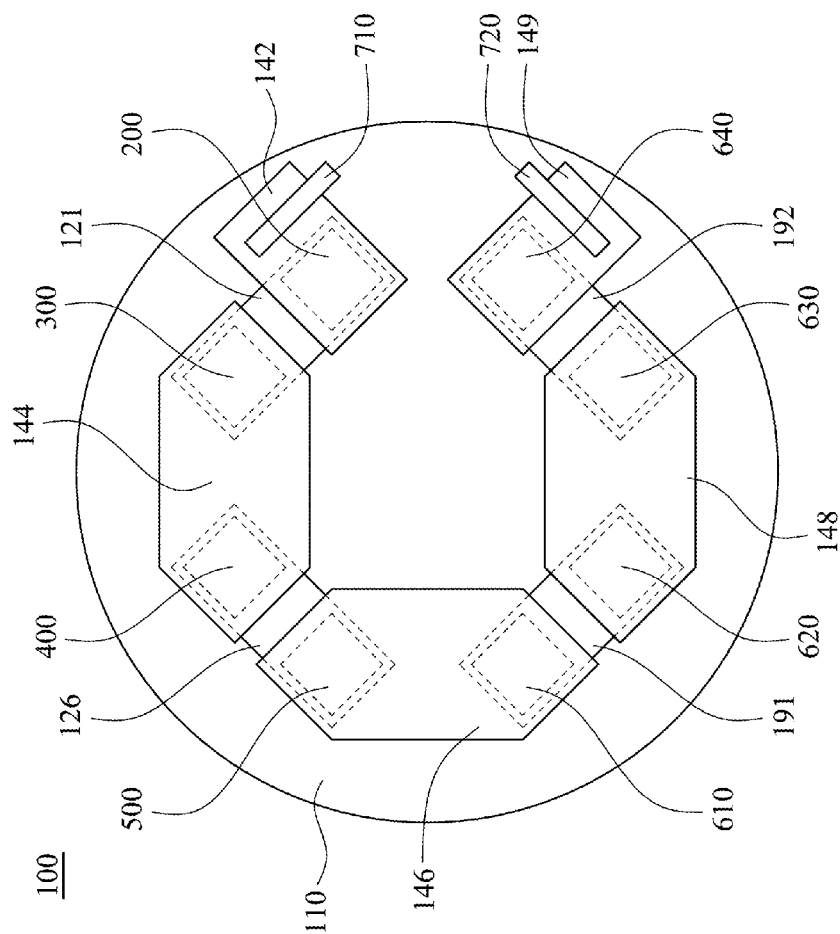


Fig. 3B

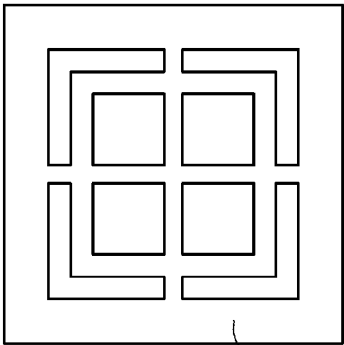


Fig. 4A

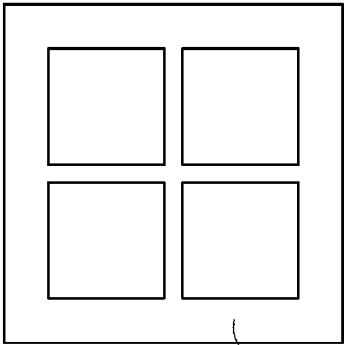
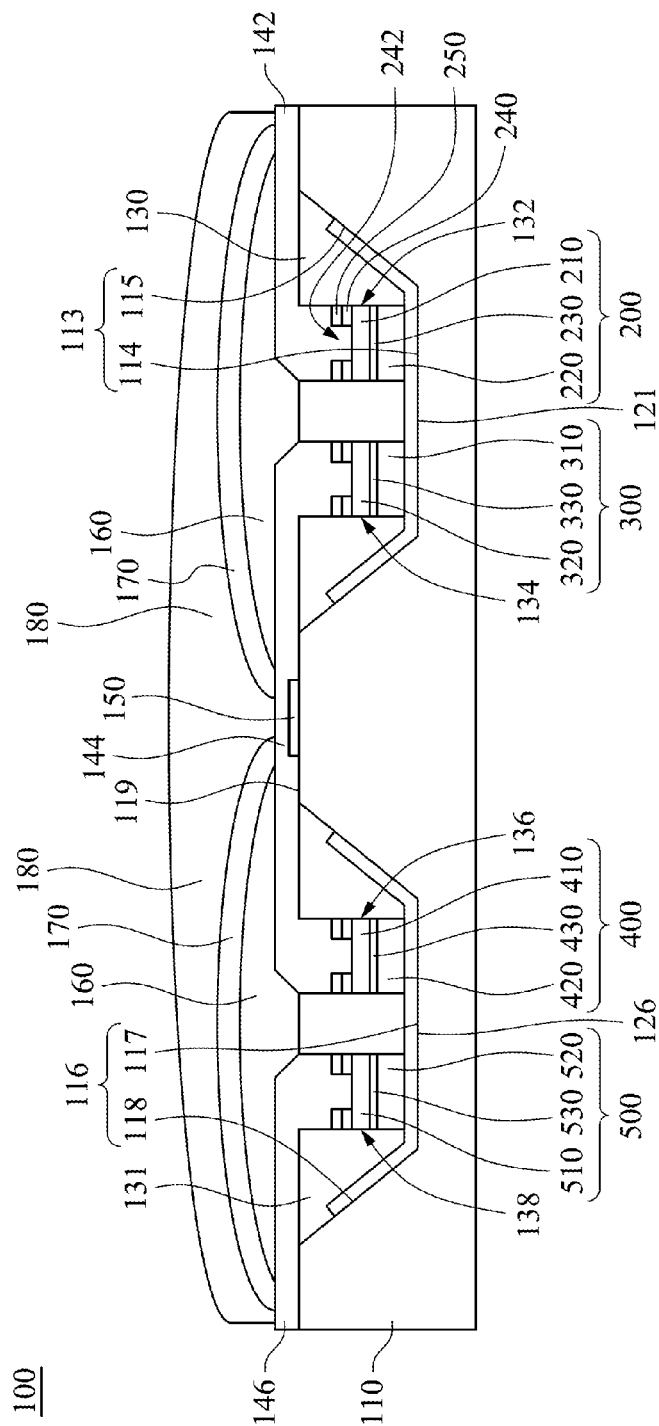


Fig. 4B

240

Fig. 4C



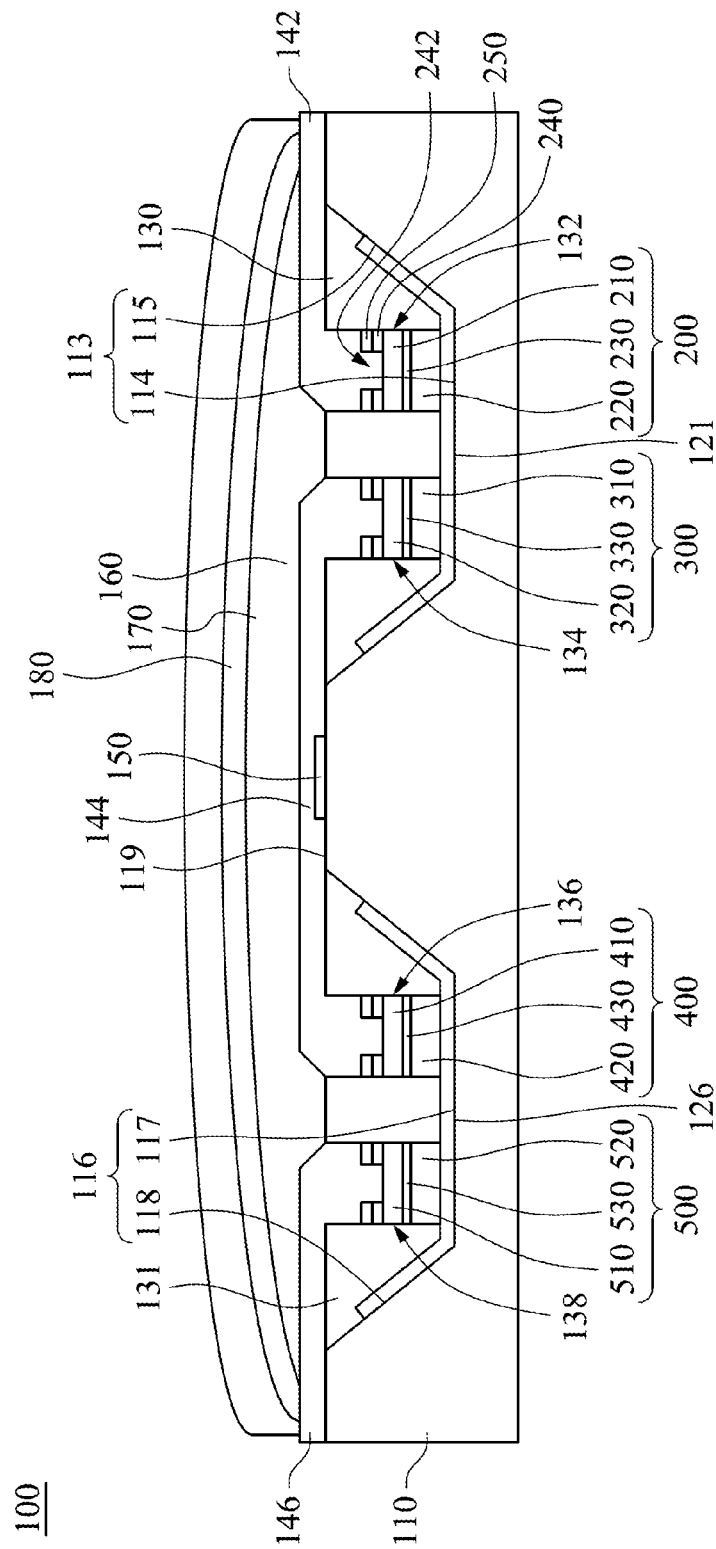


Fig. 6

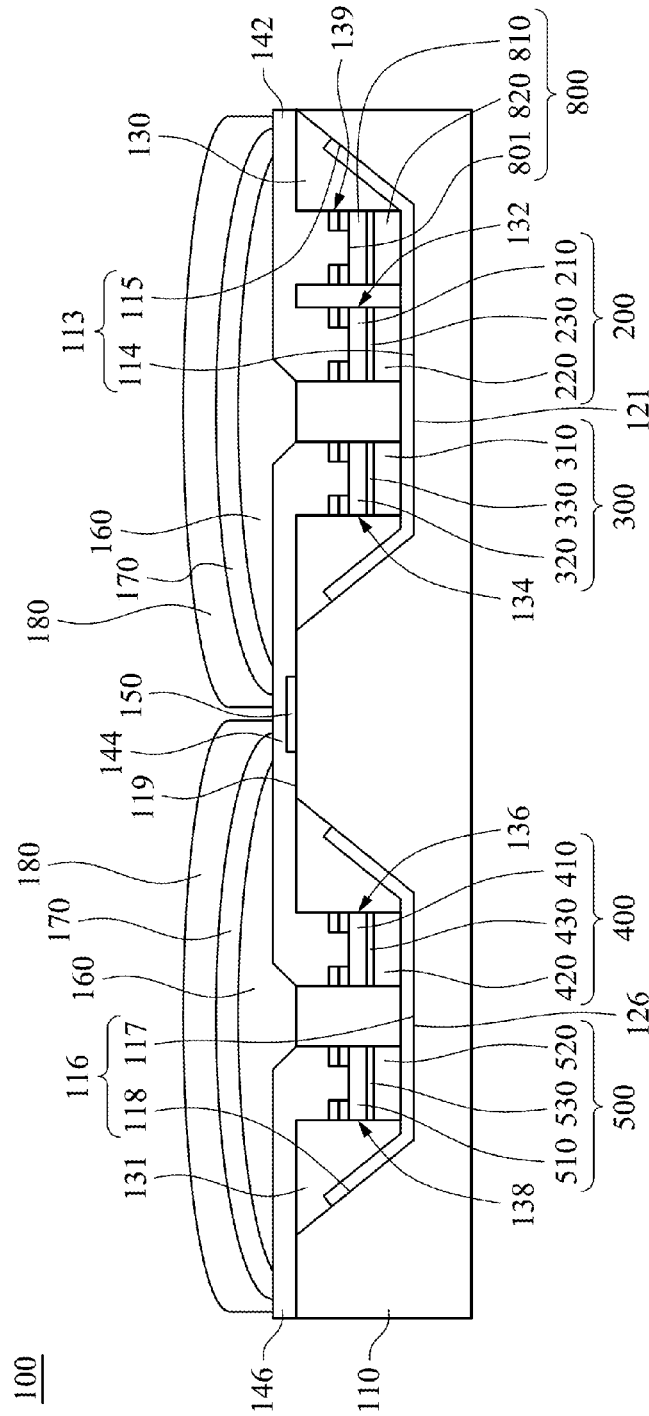


Fig. 7

LIGHT-EMITTING DIODE LIGHTING DEVICE

BACKGROUND

In recent years, light-emitting diode (LED) technologies have improved a lot, and LEDs with high power and high brightness have been presented to the market. In addition, the LEDs used as light bulbs have the advantage of long lifetime. Therefore, such LED light bulbs have the tendency to replace other conventional light sources. LEDs can be applied to various types of lamps, such as traffic lights, street lights, and flashlights.

Since LEDs gradually become mainstream light sources, improving properties of LEDs becomes an important issue, and this becomes the main goal in the R&D departments of the LED industries.

SUMMARY

This disclosure provides a light-emitting diode (LED) lighting device to achieve high power, high luminous efficiency, and longer lifetime.

In one aspect of the disclosure, a LED lighting device is provided. The light-emitting diode (LED) lighting device includes a substrate, at least one first bottom electrode, a bottom transparent isolation layer, at least one first vertical LED, at least one second vertical LED, a first top transparent electrode, and a second top transparent electrode. The substrate has at least one first recess therein, in which the first recess has a bottom surface and at least one tapered side surface adjacent to the bottom surface. The first bottom electrode is disposed in the first recess, in which the first bottom electrode is reflective and covers at least a part of the bottom surface and at least a part of the tapered side surface. The first vertical LED is disposed in the first recess and on the first bottom electrode. The second vertical LED is disposed in the first recess and on the first bottom electrode. The first bottom transparent isolation layer is disposed in the first recess, in which the first bottom transparent isolation layer has a first opening and a second opening therein to respectively expose at least a part of the first vertical LED and at least a part of the second vertical LED. The first top transparent electrode is electrically connected to the first vertical LED through the first opening. The second top transparent electrode is electrically connected to the second vertical LED through the second opening, in which the first top transparent electrode, the second top transparent electrode, and the first bottom electrode cooperate to electrically connect the first vertical LED and the second vertical LED in series.

By electrically connecting the first vertical LED and the second vertical LED in series, the LED lighting device can achieve high power and high luminous efficiency by electrically connecting to a power supply with high voltage. In addition, the current passing the first vertical LED and the second vertical LED needs not to be large to achieve high power and high luminous efficiency. Therefore, the lifetime of the first vertical LED and the second vertical LED may be longer, and cooling may not become a problem.

It is to be understood that both the foregoing general description and the following detailed description are by examples, and are intended to provide further explanation of the invention as claimed.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention can be more fully understood by reading the following detailed description of the embodiment, with reference made to the accompanying drawings as follows:

FIG. 1 is a schematic cross-sectional view of a light-emitting diode (LED) lighting device according to one embodiment of this disclosure;

FIG. 2 is a schematic cross-sectional view of the LED lighting device according to another embodiment of this disclosure;

FIG. 3A is a schematic top view of the LED lighting device according to one embodiment of this disclosure;

FIG. 3B is a schematic top view of the LED lighting device according to another embodiment of this disclosure;

FIGS. 4A to 4C are horizontal cross-sectional views of a patterned dielectric layer according to different embodiments of this disclosure;

FIG. 5 is a schematic cross-sectional view of the LED lighting device according to another embodiment of this disclosure;

FIG. 6 is a schematic cross-sectional view of the LED lighting device according to another embodiment of this disclosure; and

FIG. 7 is a schematic cross-sectional view of the LED lighting device according to another embodiment of this disclosure.

DETAILED DESCRIPTION

In the following detailed description, for purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the disclosed embodiments. It will be apparent, however, that one or more embodiments may be practiced without these specific details. In other instances, well-known structures and devices are schematically depicted in order to simplify the drawings.

FIG. 1 is a schematic cross-sectional view of a light-emitting diode (LED) lighting device 100 according to one embodiment of this disclosure. As shown in FIG. 1, an LED lighting device 100 is provided. The LED lighting device 100 includes a substrate 110, at least one bottom electrode 121, a bottom transparent isolation layer 130, at least one vertical LED 200, at least one vertical LED 300, top transparent electrodes 142 and 144. The substrate 110 has at least one recess 113 therein, and the recess 113 has a bottom surface 114 and at least one tapered side surface 115 adjacent to the bottom surface 114. The bottom electrode 121 is disposed in the recess 113. The bottom electrode 121 is reflective and covers at least a part of the bottom surface 114 and at least a part of the tapered side surface 115. The vertical LEDs 200 and 300 are disposed in the recess 113 and on the bottom electrode 121. The bottom transparent isolation layer 130 is disposed in the recess 113. The bottom transparent isolation layer 130 has openings 132 and 134 therein to respectively expose at least a part of the vertical LED 200 and at least a part of the vertical LED 300. The top transparent electrode 142 is electrically connected to the vertical LED 200 through the opening 132. The top transparent electrode 144 is electrically connected to the vertical LED 300 through the opening 134. The top transparent electrodes 142 and 144 and the bottom electrode 121 cooperate to electrically connect the vertical LEDs 200 and 300 in series.

By electrically connecting the vertical LEDs 200 and 300 in series, the LED lighting device 100 can achieve high power and high luminous efficiency. In addition, the current passing through the vertical LEDs 200 and 300 can remain small to enhance the lifetime of the vertical LEDs 200 and 300 and reduce heat generated by the vertical LEDs 200 and 300.

Specifically, for example, if the voltage difference of each of the vertical LEDs 200 and 300 is 3.125 volts, and the current passing through the vertical LEDs 200 and 300 is 1

ampere, the power of the combination of the vertical LEDs **200** and **300** is 6.25 watts. If a single LED is used to achieve the same power, the current should be 2 amperes. As a result, the single LED may have a shorter lifetime due to the larger passing current, and the cooling of the single LED may also be more difficult.

Because the LED lighting device **100** employs the top transparent electrodes **142** and **144** as its top electrode to interconnect different electronic components, a wire bonding process may not be needed. Therefore, the process yield of the LED lighting device **100** is improved, and the manufacturing cost of the LED lighting device **100** is lowered.

The substrate **110** has a high thermal conductivity. Specifically, the substrate **110** is made of silicon, such as undoped silicon, p-type silicon, or n-type silicon, or a ceramic material.

When the substrate **110** is made of silicon, the potential of the substrate **110** may be operated to be the lowest among all elements of the LED lighting device **100**, such that the contact surface of the substrate **110** and the conductive elements above the substrate **110** (for example, the bottom electrode **121** or the top transparent electrodes **142**) totally or partially form a reverse bias of p-n junction. Therefore, the substrate **110** is electrically insulated from the conductive elements above the substrate **110**.

Embodiments of this disclosure are not limited thereto. FIG. **2** is a schematic cross-sectional view of the LED lighting device **100** according to another embodiment of this disclosure. As shown in FIG. **2**, the substrate **110** includes an insulation layer **111** and a conductive layer **112**. The insulation layer **111** may be made of silicon dioxide (SiO_2), which may be oxidized from silicon. The conductive layer **112** may be made of metal such as aluminium, and the conductive layer **112** may function as a heat-dissipating layer.

The potential of the substrate **110** may be operated to be the intermediate value of the maximum potential and the minimum potential among all elements of the LED lighting device **100**, such that the potential differences between the substrate **110** and the conductive elements above the substrate **110** (for example, the bottom electrode **121** or the top transparent electrodes **142**) are not too large. Therefore, the current does not pass through the insulation layer **111**, and thus the substrate **110** is electrically insulated from the conductive elements above the substrate **110**.

The depth of the recess **113** is in a range from about 5 μm to about 50 μm . People having ordinary skill in the art can make proper modifications to the depth of the recess **113** depending on the actual application.

The angle between the bottom surface **114** and the tapered side surface **115** is in a range from about 120° to about 160°. If the substrate **110** is made of silicon and the recess **113** is formed by a wet etching process, the angle between the bottom surface **114** and the tapered side surface **115** is about 125.3°.

The bottom electrode **121** is made of metal, such as silver. Embodiments of this disclosure are not limited thereto. In other embodiments, the bottom electrode **121** is a multi-layer structure. For example, the bottom electrode **121** is a double-layer structure made of copper and silver or a triple-layer structure made of copper, titanium, and silver.

The bottom electrode **121** functions as a reflective layer to reflect light emitted from the vertical LEDs **200** and **300**, such that light emitted from the vertical LEDs **200** and **300** forwards upwardly. By the cup-shaped bottom electrodes **121**, light emitted from the vertical LEDs **200** and **300** are ensured to forward upwardly and does not forward in an unwanted direction.

The vertical LEDs **200** and **300** are in reversed electricity polarity. Specifically, the vertical LED **200** further includes a first semiconductor layer **210** proximal to the top transparent electrode **142** and a second semiconductor layer **220** proximal to the bottom electrode **121**. The vertical LED **300** further includes a first semiconductor layer **310** proximal to the bottom electrode **121** and a second semiconductor layer **320** proximal to the top transparent electrode **144**. The first semiconductor layers **210** and **310** of the vertical LEDs **200** and **300** are of the same type, and the second semiconductor layers **220** and **320** of the vertical LEDs **200** and **300** are of the same type.

More specifically, the first semiconductor layers **210** and **310** of the vertical LEDs **200** and **300** are n-type semiconductor layers, and the second semiconductor layers **220** and **320** of the vertical LEDs **200** and **300** are p-type semiconductor layers. Embodiments of this disclosure are not limited thereto. In other embodiments, the first semiconductor layers **210** and **310** of the vertical LEDs **200** and **300** are p-type semiconductor layers, and the second semiconductor layers **220** and **320** of the vertical LEDs **200** and **300** are n-type semiconductor layers.

The first semiconductor layers **210** and **310** and the second semiconductor layers **220** and **320** can be made of gallium nitride (GaN). People having ordinary skill in the art can make proper modifications to the material of the first semiconductor layers **210** and **310** and the second semiconductor layers **220** and **320** depending on the actual application.

The vertical LED **200** further includes an active layer **230** disposed between the first semiconductor layer **210** and the second semiconductor layer **220**. The vertical LED **300** further includes an active layer **330** disposed between the first semiconductor layer **310** and the second semiconductor layer **320**. Specifically, the active layer **230** and **330** can be multiple-quantum-well structures.

Specifically, the bottom transparent isolation layer **130** covers the bottom electrode **121**, such that the bottom electrode **121** is electrically isolated from the top transparent electrodes **142** and **144**.

The bottom transparent isolation layer **130** has a high refractive index. Specifically, the refractive index of the bottom transparent isolation layer **130** is larger than 1.5. The bottom transparent isolation layer **130** may reduce total reflection in the vertical LEDs **200** and **300** and thus enhance the light extraction of the vertical LEDs **200** and **300**.

The top transparent electrodes **142** and **144** are made of indium tin oxide (ITO). People having ordinary skill in the art can make proper modifications to the material of the top transparent electrodes **142** and **144** depending on the actual application.

The top transparent electrodes **142** and **144** may be patterned from a transparent conductive layer. The patterning of top transparent electrodes **142** and **144** is performed by a developing and etching process or a screen printing and etching process.

The substrate **110** further has at least one recess **116** therein. The LED lighting device **100** further includes a bottom electrode **126**, at least one vertical LED **400**, at least one vertical LED **500**, and a bottom transparent isolation layer **131**. The bottom electrode **126** is disposed in the recess **116**. The vertical LEDs **400** and **500** are disposed in the recess **116** and on the bottom electrode **126**. The bottom transparent isolation layer **131** is disposed in the recess **116**. The bottom transparent isolation layer **131** has openings **136** and **138** therein to expose at least a part of the vertical LED **400** and at least a part of the vertical LED **500**. The top transparent electrode **144** is further electrically connected to the vertical

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LED **400** through the opening **136**, and the top transparent electrode **146** is electrically connected to the vertical LED **500** through the opening **138**. The bottom electrodes **121** and **126** and the top transparent electrodes **142**, **144**, and **146** cooperate to electrically connect the vertical LEDs **200**, **300**, **400**, and **500** in series.

The vertical LEDs **300** and **400** are in reversed electricity polarity. Specifically, the vertical LED **400** includes a first semiconductor layer **410** proximal to the top transparent electrode **144** and a second semiconductor layer **420** proximal to the bottom electrode **126**. The first semiconductor layers **310** and **410** of the vertical LEDs **300** and **400** are of the same type, and the second semiconductor layers **320** and **420** of the vertical LEDs **300** and **400** are of the same type.

The vertical LEDs **400** and **500** are in reversed electricity polarity. The vertical LED **500** further includes a first semiconductor layer **510** proximal to the bottom electrode **126** and a second semiconductor layer **520** proximal to the top transparent electrode **146**. The first semiconductor layers **410** and **510** of the vertical LEDs **400** and **500** are of the same type, and the second semiconductor layers **420** and **520** of the vertical LEDs **400** and **500** are of the same type.

Similarly, the substrate **110** may further have additional recess, the LED lighting device **100** may further include additional bottom electrodes, top transparent electrodes, and vertical LEDs, and all of the vertical LEDs are electrically connected to each other in series via the bottom electrodes and the top transparent electrodes. FIG. 3A is a schematic top view of the LED lighting device **100** according to one embodiment of this disclosure. For example, as shown in FIG. 3A, the LED light device **100** further includes bottom electrodes **191** and **192**, top transparent electrodes **148** and **149**, and vertical LEDs **610**, **620**, **630**, and **640**, and the vertical LEDs **200**, **300**, **400**, **500**, **610**, **620**, **630**, and **640** are electrically connected to each other in series via the bottom electrodes **121**, **126**, **191**, and **192** and the top transparent electrodes **142**, **144**, **146**, **148**, and **149**.

The LED lighting device **100** further includes an input electrode **710** and an output electrode **720** respectively electrically connected to the top transparent electrodes **142** and **149** for allowing a power supply to be electrically connected thereto. The input electrode **710** and the output electrode **720** are single-layer structures or multi-layer structures, and the input electrode **710** and the output electrode **720** are made of conductive materials. For example, the input electrode **710** and the output electrode **720** are single-layer structures made of silver, double-layer structures made of copper and silver, or triple-layer structures made of copper, titanium, and silver. In addition, the input electrode **710**, the output electrode **720**, and the bottom electrodes **121**, **126**, **191**, and **192** may be formed in the same process.

Specifically, the shape of the substrate **110** is a cuboid, and the bottom electrodes, top transparent electrodes, and vertical LEDs are disposed in a line. Embodiments of this disclosure are not limited thereto. The shape of the substrate **110** may be a cylindrical column, a triangular prism, a cube, a cuboid, a hexagonal column, an octagonal column, or a polygon column. FIG. 3B is a schematic top view of the LED lighting device **100** according to another embodiment of this disclosure. For example, as shown in FIG. 3B, the shape of the substrate **110** is a cylindrical column, and the bottom electrodes, top transparent electrodes, and vertical LEDs are disposed in a ring.

Similarly, the shape of the substrate **110** may be a cylindrical column, a triangular prism, a cube, a cuboid, a hexagonal column, an octagonal column, or a polygon column. The shape of the bottom electrode **122**, **124**, **126**, **191**, and **192**

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may be a cylindrical column, a cube, a cuboid, a dumbbell-shaped column, or a polygon column. The shape of the LEDs **200**, **300**, **400**, **500**, **610**, **620**, **630**, and **640** may be a cylindrical column, a cube, a cuboid, a hexagonal column, an octagonal column, or a polygon column. The shape of the top transparent electrodes **142**, **144**, **146**, **148**, and **149** may be a cylindrical column, a cube, a cuboid, a hexagonal column, an octagonal column, or a polygon column. The shape of the input electrode **710** and the output electrode **720** may be a cylindrical column, a cube, a cuboid, a hexagonal column, an octagonal column, or a polygon column.

As shown in FIG. 1, the first vertical LED **200** further includes a patterned dielectric layer **240**. The patterned dielectric layer **240** is disposed between the first semiconductor layer **210** and the top transparent electrode **142**. The patterned dielectric layer **240** covers an edge portion of the first semiconductor layer **210** and has an opening **242**. The top transparent electrode **142** is electrically connected to the vertical LED **200** through the opening **242**. The function of the patterned dielectric layer **240** is to prevent the surface recombination of the vertical LED **200** and to prevent the leakage of the current through the side surface of the vertical LED **200**, thereby enhancing the luminous efficiency of the vertical LED **200**.

Specifically, the patterned dielectric layer **240** is made of silicon nitride or silicon dioxide. The patterning of the patterned dielectric layer **240** is performed by a developing and etching process or a screen printing and etching process.

The vertical LED **200** further includes a guard ring **250** disposed on the patterned dielectric layer **240**. The function of the guard ring **250** is to prevent electrostatic discharge (ESD) and to make the current in the top transparent electrode **142** spread and evenly enter the vertical LED **200**.

Specifically, the guard ring **250** is made of metal, such as silver. The patterning of the guard ring **250** is performed by a developing and etching process or a screen printing and etching process. If the shapes of the horizontal cross-sections of the patterned dielectric layer **240** and the guard ring **250** are the same, the patterning of the guard ring **250** may be used as the mask of the patterned dielectric layer **240**.

FIGS. 4A to 4C are horizontal cross-sectional views of the patterned dielectric layer **240** according to different embodiments of this disclosure. As shown in FIGS. 4A to 4C, the shape of the horizontal cross-section of the patterned dielectric layer **240** may be a ring, a ring with a cross, or a plurality of rings with a cross. The shape of the horizontal cross-section of guard ring **250** may be similar to the shape of the horizontal cross-section of the patterned dielectric layer **240**. Specifically, the shape of the horizontal cross-section of guard ring **250** may be a ring, a ring with a cross, or a plurality of rings with a cross.

As shown in FIG. 1, other vertical LEDs such as vertical LED **300**, **400**, or **500** may have patterned dielectric layer and the guard ring similar to the vertical LED **200** as well.

The LED lighting device **100** further includes an auxiliary electrode **150** disposed between the vertical LED **300** and the vertical LED **400** (or the recess **113** and the recess **116**) and electrically coupled with the top transparent electrode **144**. The auxiliary electrode **150** is made of metal. The function of the auxiliary electrode **150** is to enhance the conductivity of the top transparent electrode **144**.

The auxiliary electrode **150** is isolated from the bottom electrodes **121** and **126**. The auxiliary electrode **150** and the bottom electrode **121** and **126** can be patterned from a metal layer. The patterning of the auxiliary electrode **150** and the bottom electrode **121** and **126** is performed by a developing and etching process or a screen printing and etching process.

The LED lighting device **100** further includes at least one top transparent isolation layer **160** covering at least one of the recesses **113** and **116** and at least one of the vertical LEDs **200**, **300**, **400**, and **500**. The top transparent isolation layer **160** has a high refractive index. Specifically, the refractive index of the top transparent isolation layer **160** is greater than 1.5. The refractive index of the bottom transparent isolation layer **130** is greater than or equal to the refractive index of top transparent isolation layer **160**. The top transparent isolation layer **160** may reduce total reflection in the LED light device **100** and thus enhance the light extraction of the vertical LEDs **200**, **300**, **400**, and **500**.

Specifically, a part of the top transparent isolation layer **160** covers the recess **113** and the vertical LED **200** and **300**, and another part of top transparent isolation layer **160** covers the recess **116** and the vertical LEDs **400** and **500**.

In some embodiments, the number of the top transparent isolation layers **160** is at least two, and the top transparent isolation layers **160** are stacked. The refractive indices of the top transparent isolation layers **160** increase toward the vertical LEDs **200** and **300** or the vertical LEDs **400** and **500**, and the number of the top transparent isolation layers **160** is up to 5.

The material of the top transparent isolation layer **160** may be the same as the material of the bottom transparent isolation layer **130**. People having ordinary skill in the art can make proper modifications to the material of the top transparent isolation layer **160** depending on the actual application.

The LED lighting device **100** further includes a phosphor layer **170** disposed on the top transparent isolation layer **160** and covering at least one of the recesses **113** and **116** and at least one of the vertical LEDs **200**, **300**, **400**, and **500**.

Specifically, a part of the phosphor layer **170** covers the recess **113** and the vertical LED **200** and **300**, and another part of the phosphor layer **170** covers the recess **116** and the vertical LEDs **400** and **500**.

The refractive index of the bottom transparent isolation layer **130** is greater than or equal to the refractive index of the phosphor layer **170**, and the refractive index of the top transparent isolation layer **160** is greater than or equal to the refractive index of the phosphor layer **170**.

The top transparent isolation layer **160** is shaped to allow optical path lengths from at least one of the vertical LEDs **200**, **300**, **400**, and **500** through different portions of the phosphor layer **170** to be substantially the same. Specifically, the top transparent isolation layer **160** is substantially dome shaped. Therefore, the color of the light passing the phosphor layer **170** is even. The situation that the color of some of the light passing the phosphor layer **170** is yellowish and the color of the other of the light passing the phosphor layer **170** is bluish is avoided.

The LED lighting device **100** further includes an encapsulation layer **180** disposed on the phosphor layer **170**. The encapsulation layer **180** covers at least one of the recesses **113** and **116** and at least one of the vertical LEDs **200**, **300**, **400**, and **500**. Specifically, a part of the encapsulation layer **180** covers the recess **113** and the vertical LEDs **200** and **300**, and another part of the encapsulation layer **180** covers the recess **116** and the vertical LEDs **400** and **500**. Embodiments of this disclosure are not limited thereto. FIG. **5** is a schematic cross-sectional view of the LED lighting device **100** according to another embodiment of this disclosure. As shown in FIG. **5**, the encapsulation layer **180** integrally covers the recesses **113** and **116** and the vertical LEDs **200**, **300**, **400** and **500**.

FIG. **6** is a schematic cross-sectional view of the LED lighting device **100** according to another embodiment of this disclosure. As shown in FIG. **6**, the top transparent isolation

layer **160** integrally covers the recesses **113** and **116** and the vertical LEDs **200**, **300**, **400** and **500**. The phosphor layer **170** integrally covers the recesses **113** and **116** and the vertical LEDs **200**, **300**, **400** and **500**. The encapsulation layer **180** integrally covers the recesses **113** and **116** and the vertical LEDs **200**, **300**, **400** and **500**.

Each of the aforementioned vertical LEDs may be electrically connected to additional vertical LEDs in parallel via the top transparent electrode and the bottom electrode. FIG. **7** is a schematic cross-sectional view of the LED lighting device **100** according to another embodiment of this disclosure. For example, as shown in FIG. **7**, the LED lighting device **100** further includes a vertical LED **800** disposed on the bottom electrode **121**. The bottom transparent isolation layer **130** further has an opening **139** therein to expose at least a part **801** of the vertical LED **800**, the top transparent electrode **142** is further electrically connected to the vertical LED **800** through the opening **139**, and the top transparent electrode **142** and the bottom electrode **121** cooperate to electrically connect the vertical LEDs **200** and **800** in parallel.

Specifically, The vertical LED **800** includes a first semiconductor layer **810** proximal to the top transparent electrode **142** and a second semiconductor layer **820** proximal to the bottom electrode **121**. The first semiconductor layers **210** and **810** of the vertical LEDs **200** and **800** are of the same type, and the second semiconductor layers **220** and **820** of the vertical LEDs **200** and **800** are of the same type.

Additionally, the number of the vertical LEDs in the recess **113** and the number of the vertical LEDs in recess **116** may be the same or different. For example, as shown in FIG. **1**, the number of the vertical LEDs in the recess **113** is two, and the number of the vertical LEDs in recess **116** is two as well. As shown in FIG. **7**, the number of the vertical LEDs in the recess **113** is three, and the number of the vertical LEDs in recess **116** is two.

By electrically connecting the vertical LEDs in series, the LED lighting device **100** can achieve high power and high luminous efficiency by electrically connecting to a power supply with high voltage. In addition, the current passing the vertical LEDs needs not to be large to achieve high power and high luminous efficiency. Therefore, the lifetime of the vertical LEDs may be longer, and cooling may not become a problem.

All the features disclosed in this specification (including any accompanying claims, abstract, and drawings) may be replaced by alternative features serving the same, equivalent or similar purpose, unless expressly stated otherwise. Thus, unless expressly stated otherwise, each feature disclosed is one example only of a generic series of equivalent or similar features.

Any element in a claim that does not explicitly state "means for" performing a specified function, or "step for" performing a specific function, is not to be interpreted as a "means" or "step" clause as specified in 35 U.S.C. §112, 6th paragraph. In particular, the use of "step of" in the claims herein is not intended to invoke the provisions of 35 U.S.C. §112, 6th paragraph.

What is claimed is:

1. A light-emitting diode (LED) lighting device, comprising:
 - a substrate having at least one first recess and at least one second recess therein, wherein the first recess has a bottom surface and at least one tapered side surface adjacent to the bottom surface, and the substrate is made of one piece of material;
 - at least one first bottom electrode disposed in the first recess, wherein the first bottom electrode is reflective

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and covers at least a part of the bottom surface and at least a part of the tapered side surface;
 at least one first vertical LED disposed in the first recess and on the first bottom electrode;
 at least one second vertical LED disposed in the first recess and on the first bottom electrode;
 a first bottom transparent isolation layer disposed in the first recess, wherein the first bottom transparent isolation layer has a first opening and a second opening therein to respectively expose at least a part of the first vertical LED and at least a part of the second vertical LED;
 a first top transparent electrode electrically connected to the first vertical LED through the first opening;
 a second top transparent electrode electrically connected to the second vertical LED through the second opening, wherein the first top transparent electrode, the second top transparent electrode, and the first bottom electrode cooperate to electrically connect the first vertical LED and the second vertical LED in series;
 a second bottom electrode disposed in the second recess; at least one third vertical LED disposed in the second recess and on the second bottom electrode; and
 a second bottom transparent isolation layer disposed in the second recess, wherein the second bottom transparent isolation layer has a third opening therein to expose at least a part of the third vertical LED, wherein the second top transparent electrode is further electrically connected to the third vertical LED through the third opening, and the first bottom electrode, the second top transparent electrode, and the second bottom electrode cooperate to electrically connect the second vertical LED and the third vertical LED in series.

2. The LED lighting device of claim 1, wherein the first vertical LED comprises:
 a first semiconductor layer proximal to the first top transparent electrode; and
 a second semiconductor layer proximal to the first bottom electrode; and
 the second vertical LED comprises:
 a first semiconductor layer proximal to the first bottom electrode; and
 a second semiconductor layer proximal to the second top transparent electrode, wherein the first semiconductor layers of the first vertical LED and the second vertical LED are of the same type, and the second semiconductor layers of the first vertical LED and the second vertical LED are of the same type.

3. The LED lighting device of claim 1, wherein the first bottom electrode is made of metal.

4. The LED lighting device of claim 1, wherein the first bottom electrode is a multi-layer structure.

5. The LED lighting device of claim 1, further comprising:
 a third vertical LED disposed in the first recess and on the first bottom electrode, wherein the first bottom transparent isolation layer has a third opening therein to expose at least a part of the third vertical LED, the first top transparent electrode is further electrically connected to the third vertical LED through the third opening, and the first top transparent electrode and the first bottom electrode cooperate to electrically connect the first vertical LED and the third vertical LED in parallel.

6. The LED lighting device of claim 5, wherein the first vertical LED comprises:
 a first semiconductor layer proximal to the first top transparent electrode; and

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a second semiconductor layer proximal to the first bottom electrode; and
 the third vertical LED comprises:
 a first semiconductor layer proximal to the first top transparent electrode; and
 a second semiconductor layer proximal to the first bottom electrode, wherein the first semiconductor layers of the first vertical LED and the third vertical LED are of the same type, and the second semiconductor layers of the first vertical LED and the third vertical LED are of the same type.

7. The LED lighting device of claim 1, wherein the second vertical LED comprises:
 a first semiconductor layer proximal to the first bottom electrode; and
 a second semiconductor layer proximal to the second top transparent electrode;
 the third vertical LED comprises:
 a first semiconductor layer proximal to the second top transparent electrode; and
 a second semiconductor layer proximal to the second bottom electrode, wherein the first semiconductor layers of the second vertical LED and the third vertical LED are of the same type, and the second semiconductor layers of the second vertical LED and the third vertical LED are of the same type.

8. The LED lighting device of claim 1, further comprising:
 at least one auxiliary electrode disposed between the second vertical LED and the third vertical LED and electrically coupled with the second top transparent electrode, wherein the auxiliary electrode is made of metal.

9. The LED lighting device of claim 8, wherein the auxiliary electrode is isolated from the first bottom electrode and the second bottom electrode.

10. The LED lighting device of claim 8, wherein the auxiliary electrode is disposed between the first recess and the second recess.

11. The LED lighting device of claim 1, wherein the first vertical LED comprises:
 a first semiconductor layer proximal to the first top transparent electrode;
 a second semiconductor layer proximal to the first bottom electrode;
 an active layer disposed between the first semiconductor layer and the second semiconductor layer; and
 a patterned dielectric layer disposed between the first semiconductor layer and the first top transparent electrode and covering an edge portion of the first semiconductor layer.

12. The LED lighting device of claim 11, wherein the first vertical LED further comprises:
 a guard ring disposed on the patterned dielectric layer.

13. The LED lighting device of claim 1, further comprising:
 at least one top transparent isolation layer covering at least one of the first vertical LED and the second vertical LED.

14. The LED lighting device of claim 13, wherein the refractive index of the first bottom transparent isolation layer is greater than or equal to the refractive index of the top transparent isolation layer.

15. The LED lighting device of claim 13, wherein the refractive indices of a plurality of the top transparent isolation layers increase towards the first vertical LED and the second vertical LED.

16. The LED lighting device of claim 1, further comprising:

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a phosphor layer covering at least one of the first vertical LED and the second vertical LED.

17. The LED lighting device of claim 16, wherein the phosphor layer covers at least the first recess.

18. The LED lighting device of claim 16, wherein the refractive index of the first bottom transparent isolation layer is greater than or equal to the refractive index of the phosphor layer.

19. The LED lighting device of claim 16, wherein optical path lengths from at least one of the first vertical LED and the second vertical LED through different portions of the phosphor layer are substantially the same.

20. The LED lighting device of claim 16, further comprising:

at least one top transparent isolation layer disposed between the phosphor layer and the first bottom transparent isolation layer, wherein the top transparent isolation layer is shaped to allow optical path lengths from at

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least one of the first vertical LED and the second vertical LED through different portions of the phosphor layer to be substantially the same.

21. The LED lighting device of claim 20, wherein the refractive index of the top transparent isolation layer is greater than or equal to the refractive index of the phosphor layer.

22. The LED lighting device of claim 20, further comprising:

an encapsulation layer disposed on the phosphor layer, wherein the encapsulation layer covers at least one of the first recess and the second recess.

23. The LED lighting device of claim 1, further comprising:

an encapsulation layer covering at least one of the first recess and the second recess.

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